ON DISTRIBUTIONS OF NUCLEI IN DUST–FREE WET AIR, AND ON METHODS OF OBSERVATION.[1]

By C. BARUS.

1. *Nuclei.*—The author remarks that the experiments described all refer to air, from which the ordinary or Aitken nuclei have been removed by filtration. The air is carefully kept saturated with water vapor, and examined in a plug-cock fog chamber by rapid exhaustion, partly without further interference, partly when acted on by the X-rays or the beta and gamma rays or radium, entering the fog chamber from without. The radium was sealed in an aluminium tube. Water nuclei when not themselves the subject of observation (as in § 6) were always scrupulously precipitated.

The kind of nuclei to be considered are thus, first, the vapor nuclei (colloidal nuclei) of dust free wet air, which are probably aggregates of water molecules; second, the ions produced by the presence of the radiant field, natural or artificial; third, water nuclei produced in dust free wet air by the evaporation of fog particles. A careful distinction is here to be made between water nuclei obtained from the evaporation of fog particles precipitated on solutional nuclei, on vapor nuclei, and on ions.

2. *Methods of Observation.*—The number of nuclei was computed from the angular diameter of the coronas of cloudy condensation. These were standardized, as shown in the author's earlier papers, by successive exhaustions, each of the same amount, the residual number of nuclei (after correction for subsidence) decreasing in geometric progression with the number of exhaustions. New experiments were deemed desirable for the present work and were carried out at great length.

To measure the angular diameters of the coronas the older

[1] Extract of certain investigations made by aid of a grant obtained from the Carnegie Institution.

method of a single point of light and a goniometer of special type on opposed sides of the fog chamber was first used. Figs. 2 and 3 give examples of these results.

Subsequently a new method was devised, in which two identical sources of light equidistant from the eye, were moved symmetrically toward and from each other, on a line parallel to the axis of the fog chamber. Observation consisted in placing the fiducial annuli of each of the two coronas in contact, by adjusting the lights at a distance S apart. A lever for this purpose is in the hands of the observer. The normal distance between S and the fog chamber being R and θ the angle of diffraction, $S = 2R \tan \theta$. The advan-
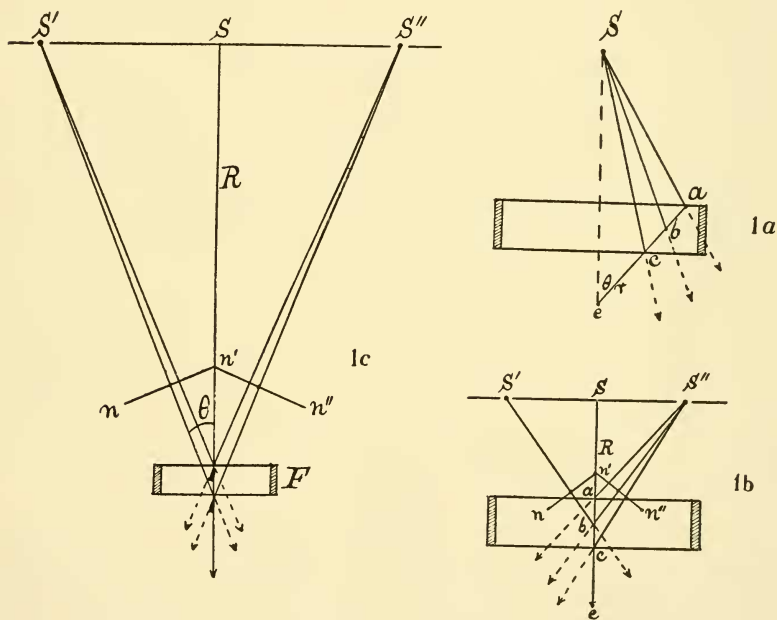

Fig.1

Fig. 1a. Diffractions from a single source S from fog particles a, b, c, within the fog chamber, suggesting changes of the angle of diffraction to an eye at c. r is the radius of the goniometer.

Fig. 1b. Diffractions from two sources S' and S'' from fog particles at a, b, and c, within the fog chamber. Coronas nn' and $n'n''$ in contact.

Fig. 1c. The same drawn to scale. Fog chamber at F. Angles of diffraction shaded. Coronas nn', $n'n''$.

tage of this method of contact consists in this, that the observed diffracton takes place in the equatorial plane of the fog chamber; there is less obliquity of rays, and coronas of any size are observable . (an essential condition since the angle for the large coronas approaches 60°), and both eyes may be used, placed all but in contact with the fog chamber. This diminishes the eyestrain and insures sharper vision. Lantern slides were shown giving all the details of this apparatus. The accompanying diagrams $1a$ and $1b$ indicate the differences of the old and new method and the latter is additionally elucidated in figure $1c$.

3. *The Green Coronas.*—If the coronas be divided into two general types, those which have red discs or red primary annuli, and those in which the discs are green, the latter are convenient for comparison. In successive identical exhaustions they occur at regular intervals and among the larger coronas three successive series are particularly vivid, corresponding to fog particles whose diameters are $d_4 = .00052$, $d_3 = .00040$, $d_2 = .00023$ cm. These numbers may be regarded as in the ratio of 4, 3, and 2, and they suggest a first series with $d_1 = .00013$ as the highest type. The author has not been able to obtain this in any case whatever; but the red type of the first series is well produceable and is the first of a succession of diameters of fog particles, $d_1 = .00016$, $d_2 = .00032$, $d_3 = .00048$, $d_4 = .00064$, etc. The angular diameter of d_1 is about 60° showing the enormous size of the coronas in question. The occurrence of the first series is corroborated by the axial colors of the steam jet.

4. *Wilson's Conclusions as to Size and Number of Fog Particles.*—In the preceding section the conclusion was reached, that the smallest corona-producing fog particles must exceed the order of size, .0001 cm. Mr. C. T. R. Wilson believes that when " all diffraction colors disappear and the fog appears white from all points of view (adiabatic expansion 1.44) . . . the diameter of the drops does not exceed one wave length of light, or 50×10^{-6} cm." What Wilson refered to is probably the filmy disc of the red corona, of the order of $d_1 = .00016$ cm. It is therefore probable that Wilson's final greenish white color corresponded to about 10^6 nuclei, or that the filmy white implies two or three million nuclei, rather than

to 10^8 vapor nuclei per cubic centimeter as he asserts. Compare section 5.

5. *Distribution of Vapor Nuclei and of Ions in Dust-free Air.*— On March second the author gave a resumé of certain typical results to the American Physical Society. Distributions were there given in terms of an unsatisfactory expansion · variable, $(\delta p - (\pi - \pi_1))/(p - \pi)$, involving vapor pressure, π, as well as the drop in pressure, δp, from the atmospheric pressure p. In the present graphs these results and the new data specified will be given in terms of the relative adiabatic drop $\delta p/p$, as a more appropriate
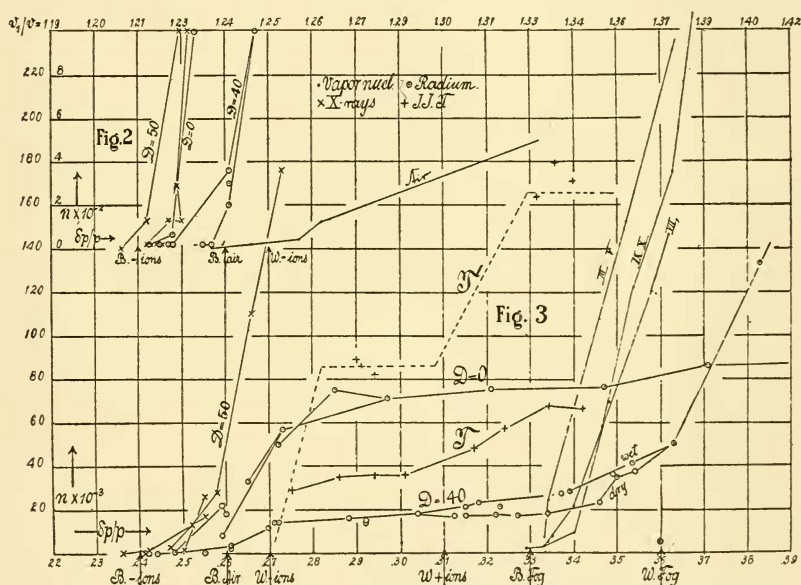
FIGS. 2 and 3. Distribution of nucleation (*n* nuclei per cubic cm.) for different drops of pressure δp adiabatically from p, or volume expansion v_1/v. Series III to X were found with dust free air not energised at different times and temperatures. D refers to the distance of the radiant tube or X-ray bulb from the fog chamber. T and T' show the results of J. J. Thomson. W refers to Wilson's fog limits, B to those of the writer. Figure 2 is an enlarged detail of figure 3 refering in particular to the regions of ions.

variable for the plug-cock fog chamber. The adiabatic volume expansion is then

$$(v_1/v)^\gamma = 1/(1 - \delta p/p),$$

increasing with $\delta p/p$. Numerically $(v_1/v) - 1$ is not very different from $\delta p/p$.

The charts contain an exhibit both of the older results and of new results. In the former the effect of rise of temperature in increasing the available nucleation to the extent of 5–10 per cent. per degree C., is marked. The earlier results are given in Figures 2 and 3.

In the new series (Figs. 4 and 5) and in case of vapor nuclei, the efficiency of the fog chamber breaks down above the green corona at about 1.5×10^6 nuclei per cubic centimeter; $\delta p/p = .41$; $v_1/v = 1.45$. Below this, the graph showing distribution and size of nuclei is well given, ascending definitely from about $\delta p/p = .31$, $v_1/v = 1.30$, which may be called the fog limit. Finally the region of ions appears as a well marked feature of the curve, extending from about $\delta p/p = .31$ to $\delta p/p = .262$, $v_1/v = 1.24$, where condensation begins (negative ions) for vapor nuclei. This is definitely below Wilson's point $v_1/v = 1.25$, for negative ions.

Exposed to the beta and gamma rays of Radium ($10,000\times$, 300 mg.), the limiting ionization observed is below 200,000 nuclei per cubic centimeter; exposed to radium ($10,000 \times$, 700 mg.), it is below 300,000 nuclei per cubic centimeter; but the condensation begins at $\delta p/p = .26$, or somewhat below $v_1/v = 1.23$, distinctly below the case for dust-free wet air.

The X-rays finally lower this condensation limit still further to $\delta p/p = .247$, or somewhat below $v_1/v = 1.223$, definitely below the point for the weak radium radiation. As compared with the curve for vapor nuclei the steepness of the X-ray curve with strong radiation, its almost sudden ascent is a further feature. It does not however, in my apparatus, get above the large green corona; *i. e.*, about 10^6 nuclei per cubic centimeter are caught at $\delta p/p = .29$, or $v_1/v = 1.27$.

One may notice, therefore, that the plug cock fog chamber puts both condensation points as well as the corresponding distribution of vapor nuclei, definitely *below* the values obtained by Wilson in his piston apparatus (marked W in the charts 2 and 3, 4 and 5). Moreover the march of the limits of condensation due to a given
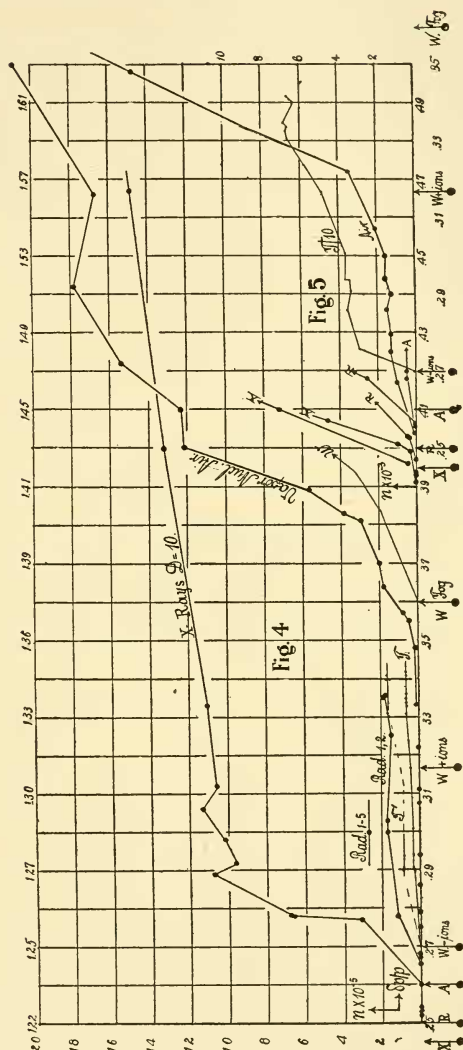
FIGS. 4 and 5. Results essentially like the cases of figures 2 and 3 but obtained by the method of two sources. The scale of nucleation is more compressed (ordinates $n \times 10^{-5}$). X, R, A, show the points at which condensation on ions produced by strong X-rays, by radium, and by natural radiation (dust free air) were observed. W refers to Wilson's results. Figure 5 is an enlargement of figure 4 in the region of ions or for low values of $\delta p/p$. T shows the results of J. J. Thomson.

radiation as compared with a maximum number of ions produced
by that radiation is as follows;

natured radiation, air......... $v_1/v = 1.24$ $n \times 10^{-3} = 1.5$
Beta and gamma rays used.... $= 1.225$ $= 100 — 150$
X-rays used................. $= 1.220$ $= 10^6 \ldots 2 \times 10^6$

Since the intensity of radiation is as the square of the number of
nuclei, an increase of the intensity of radiation from 1 to 10^4 and
from 1 to 10^6 lowers the condensation limit $(v_1/v = 1.24)$, 1.2%
and 1.6%, respectively.

6. *Residual Water Nuclei. Behavior on Successive Evapora-
tion of Fog Particles.*—Water nuclei are obtained by the evapora-
tion of fog particles, on compression of the dust-free wet air in which
they are suspended. One may expect them to differ with the nucleus
or ion on which the fog particle is precipitated, and this is the case.
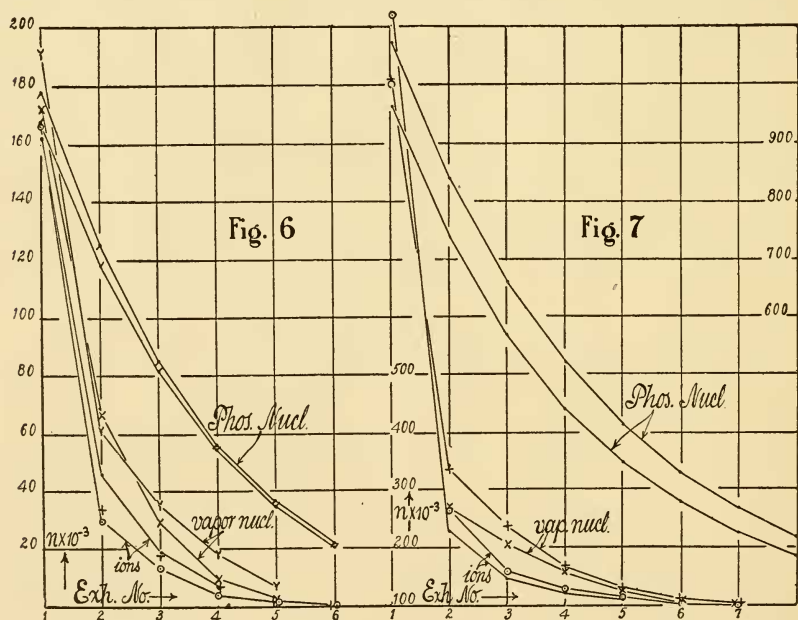
Figs. 6 and 7. The ordinates show the nucleation (*n* nuclei per cubic
cm.) obtained upon successive identical exhaustions and immediate evapora-
tion, thereafter, of the fog particles precipitated. The abscissas give the
number of exhaustions. The ions, the vapor nuclei of dust free air and
phosphorus, or solutional nuclei are contrasted. In the latter case, removal
by exhaustion is the only source of loss.

The best method of discriminating between water nuclei was found to be the successive evaporation of fog particles precipitated on the same nuclei under identical exhaustions, until the nuclei are wholly removed by the exhaustion and subsidence. The results may be exhibited in graphs, in which for about the same number of initial nuclei, the persistence of the corresponding water nuclei is shown by the number of nuclei which survive after successive evaporations, in case of phosphorus nuclei, vapor nuclei and ions. Compare figures 6 and 7.

In case of phosphorus nuclei, after z identical exhaustions, the number of nuclei n_z remaining is given by

$$n_z = n_1 y^{z-1} \Pi,$$

where n_1 is the initial number of nuclei per cubic centimeter, y the exhaustion ratio and the product, Π, the correction for subsidence; but if ions or vapor nuclei are used, an additional coefficient of loss x must be allotted to each exhaustion, so that

$$n_z = n_1 y^{z-1} x^{z-1} \Pi.$$

The following example shows this clearly.

TABLE I.

	Ions.					Water Nuclei.			
z	$n \times 10^{-3}$	$n' \times 10^{-3}$	x	$(n'-n)/n$	z	$n \times 10^{-3}$	$n' \times 10^{-3}$	x	$(n'-n)/n$
1	166	166	1.00	0	1	172	172	1.00	0
2	29	117	.25	3.0	2	66	120	.55	.8
3	13	64	.45	3.9	3	29	77	.62	1.7
4	4	25	.53	5.7	4	9	42	.60	3.6
5	1	10	.80	8.5	5	2	12	.66	4.8
1	810	813	1.00	0	1	905	905	1.00	0
2	115	607	.19	4.3	2	166	673	.25	3.0
3	44	415	.48	8.4	3	103	473	.47	3.6
4	18	245	.52	12.5	4	57	319	.56	4.6
5	6	112	.47	18.5	5	24	201	.59	7.8

The exhaustion loss, x, is thus greater in the second exhaustion, or after the first evaporation of fog particles, three fourths to four fifths of the number of fog particles precipitated on ions vanishing, while one half to three quarters of the number of fog particles precipitated upon vapor nuclei vanish in the first evaporation, according as the initial number is smaller or greater. The exhaustion loss x is also greater for the case of precipitation on ions, as compared with the precipitation on water nuclei.

Since x is not constant the equation for the second exhaustion should read $n_1 y . x \Pi_1$; for the third $n_1 y^2 . x x' \Pi_2$; etc.

It will then be found that for ions

| $x = .25$ | $x' = .80$ | $x'' = .76$, etc. |
| $x = .19$ | $x' = 1.20$ | $x'' = .62$, etc. |

For water nuclei

| $x = .55$ | $x' = .70$ | $x'' = .57$, etc. |
| $x = .25$ | $x' = .88$ | $x'' = .80$, etc. |

data which are somewhat irregular, but accentuate the importance of the first evaporation.

Special experiments showed that the loss in question is specifically due to the evaporation, and not to time, as, for instance, the loss by diffusion of small nuclei would be. If the time interval between exhaustions is doubled or trebled, etc., there is no corresponding difference in the result.

7. *Decay of Ionized Nuclei in the Lapse of Time.*—If n be the number of nuclei per cubic centimeter, a the number generated per second by the radiant field, bn^2 the number decaying per second, $dn/dt = a - bn^2$. If the radiation is cut off t seconds before exhaustion, $a = 0$, $dn/dt = - bn^2$ or $1/n = 1/n_0 + b(t - t_0)$. Thus the relative nucleation may be found if b is known. If n_0/n is also known, given for instance by the above method of geometric sequences, the absolute nucleation $n_0 = ((n_0/n) - 1)/b(t - t_0)$ is determinable.

The result of this apparently straightforward method leads to grave complications, inasmuch as b is not constant but increases rapidly as the number of nuclei is smaller. Its value moreover is usually twice as large as the electrical coefficient $b = 1.4 \times 10^{-6}$. Thus in Table II,

TABLE II.

n	t	$b \times 10^6$	$b^1 \times 10^6$
83	0	2.9	3.8
38	5	2.1	4.1
27	10	3.3	5.7
14.3	20	4.2	13.4
9.0	30	3.5	
4.6	60	15.0	
1	120		

[1] By taking the first and fourth observations, etc.

which is an example chosen at random from many similar cases. The mean b (excluding the last) is thus .000,0045, at least three times as large as the electrical coefficient.

.   If but a part n of the nuclei are caught by the exaustion, n' escaping, $-dn/dt - dn'/dt = bn^2 + 2bnn' + bn'^2$. Hence if but $1/m$ of all the ions are captured, the coefficient of decay, b, found should be about m times too large as compared with the true value, or $dn/dt = - mbn^2$. But this fails to explain the increase of b with $1/n$, unless the nuclei grow smaller during decay (or virtually by loss of charge) and so pass beyond the scope of exhaustion. But this is improbable; the experiments show that b increases while the number of nuclei present decreases, no matter whether these reduced numbers of nuclei are due to weak radiation (generating but a few), or to low exhaustion (catching but a few), or to the decay of a larger nucleation (where only a few survive in the lapse of time). If $-dn/dt = -a + cn + bn^2$, where a is the number of ions generated per second by the radiation, cn the number independently absorbed per second and bn^2 the decay per second by mutual destruction, the integrated equation very fully reproduces the observed nucleations n, when $b = .000001$ and $c = .0356$.

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